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Effectiveness of surface coatings in improving concrete durability

A.A. Almusallam *, F.M. Khan, S.U. Dulaijan, O.S.B. Al-Amoudi

Department of Civil Engineering, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia

Abstract

This paper reports results of a study conducted to evaluate the durability of concrete coated with concrete surface coatings representing five generic types. The durability of the uncoated and coated concrete specimens was evaluated by assessing water absorption, chloride permeability and chloride diffusion. The chemical resistance was evaluated by immersing the uncoated and coated mortar specimens in 2.5% sulfuric acid. The results indicated that epoxy and polyurethane coatings performed better than acrylic, polymer and chlorinated rubber coatings. However, noticeable variation in the performance of the same generic type procured from different manufacturers was noted. Therefore, the selection of coatings should be done after conducting trial tests rather than basing it solely on the generic type.

Keywords: Surface coatings; Concrete durability; Chemical resistance

1. Introduction

The necessity for providing supplementary protection to concrete in situations where the structures are exposed to aggressive environments is now well appreciated. Several researchers [1–3] have attributed premature deterioration of concrete exposed to severe environments to the unrealistic evaluation of the severity of the service-environment. As a consequence, the requirement for a holistic approach to the design of a durable concrete structure has been advocated [4]. It is now realized that the economic superiority of Portland cement concrete can only be utilized by formulating materials specifications and construction practices commensurate with the severity of the service conditions.

The protection methods that are presently adopted include: (i) use of protective concrete surface coatings; (ii) use of metallic, epoxy and polymeric coatings on the steel and (iii) use of corrosion inhibitors. Some of these measures are suitable for the new concrete structures while others can be adopted for old structures as well. While coated reinforcing steel bars have been utilized in construction during the past decade there have been conflicting opinion on their usefulness, vis-à-vis, the localized corrosion at locations of coating damage. Similarly, the usefulness of concrete inhibitors in reducing reinforcement corrosion is yet to be established.

Coatings, particularly coal tar, chlorinated rubber, epoxy, etc. have been applied on the footings and piers, to avoid concrete deterioration due to sulfate attack. However, concrete coatings of several generic types are now marketted for protecting concrete at both above and below ground levels. Studies [5–8] to date have shown encouraging results on the performance of vapor barriers, vapor permeable coatings, surface penetrating sealers and protective coatings. Ibrahim et al. [9] evaluated the performance of silanes, silanes/siloxanes and acrylic coatings. In that study, the best performance was indicated by silanes/siloxanes with a top coat. Dulaijan et al. [10,11] evaluated the performance of cement- and epoxy-based coatings in protecting concrete. Results of that study [10] indicated that epoxy modified cement-based coatings provide adequate protection to concrete. However, the crack bridging capacity of the polymer modified cementitious coating was reported to be better than that of other cement-based coatings. The adhesion of all the epoxy resin-based coatings, to the concrete substrate, was noted to be better than that of the acrylic resin-based surface coatings [11]. The water permeability in the concrete specimens coated with the selected resin-based surface coatings was reported to be very low and

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* Corresponding author. Tel.: +966-3-860-4440; fax: +966-3-860-2879.

E-mail address: musallam@kfupm.edu.sa (A.A. Almusallam).

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they exhibited good crack bridging ability [11]. Further, all the coatings were noted to considerably reduce the diffusion of carbon dioxide into the concrete matrix. However, not all the coatings were able to withstand acidic exposure. The chemical-resistance of epoxy resin-based surface coatings was shown to be better than that of acrylic resin-based coatings [11].

Swamy and Tanikawa [12] evaluated the effect of surface coatings to preserve concrete durability and concluded that the application of an impervious surface coating to concrete is a very attractive solution to protect new and existing concrete structures. Sergi et al. [13] studied the influence of surface treatments on corrosion rates of steel in carbonated concrete and concluded that water-repellant surface treatments that line the pores of concrete with hydrophobic layers, were effective in resisting water penetration and limiting the corrosion rate of steel in carbonated regions in the specimens exposed to cycles of wetting and drying. Cabrera and Hassan [14] studied the effectiveness of surface treatment materials against the ingress of chloride ions into mortar and concrete and reported one of the materials tested, silane, showed signs of deterioration within the duration of the chloride permeability test. A useful summary on the related studies and the techniques utilized to evaluate the performance of surface coatings has been presented by Basheer et al. [15].

With encouraging reports on the performance of concrete surface coatings, a wide range of these, representing different generic types, are now available in the market. Under these circumstances, selection of a surface coating is all the more difficult, particularly in the absence of performance data.

This study was conducted to evaluate the performance of generic types of concrete surface coatings that are available in the market. The objective was also to assess the performance differential between two coatings representing similar generic types.

2. Experimental program

2.1. Materials and mixture proportions

Type V cement meeting ASTM C 150 requirement, was used in the preparation of concrete and mortar specimens. The chemical composition of the cement used is shown in Table 1. The specimens were prepared with a cement content of 370 kg/m^3 and water–cement ratio of 0.45. Crushed limestone with a specific gravity of 2.42, water absorption of 2.5% and a maximum size of 12.5 mm was used as the coarse aggregate. Dune sand with a specific gravity of 2.64 and absorption of 0.5% was used as the fine aggregate. In the concrete specimens, the coarse aggregate constituted 62% of the total aggregate and the rest was sand. The mortar specimens were prepared with a sand to cement ratio of 2.8.

Table 1
Chemical composition of the ASTM C 150 Type V cement used in the mortar specimens

Chemical constituent	Weight (%)
SiO_2	22.0
Al_2O_3	4.08
Fe_2O_3	4.24
CaO	64.07
MgO	2.21
SO_3	1.96
Loss of Ignition	0.8
K_2O	0.31
Na_2O	0.21
Na_2O equivalent	0.41
C_3S	54.57
C_2S	21.75
C_3A	3.50
C_4AF	12.90

2.2. Test specimens

Cylindrical concrete specimens 75 mm in diameter and 50 mm high were cast to evaluate the chloride permeability and chloride diffusion. Cement mortar specimens measuring 25 × 25 × 25 mm^3 were utilized to evaluate the chemical resistance of the selected coatings, while 50 mm diameter and 75 mm high cylindrical mortar specimens were cast to evaluate water absorption.

The concrete constituents were mixed in a revolving drum type mixer for ≈3–5 min to obtain uniform consistency. The concrete was filled in the molds in two layers and vibrated for consolidation. After casting, the specimens were covered with a wet burlap followed by a plastic sheet. They were demolded after 24 h of casting and curing was continued for two weeks. The burlaps were wetted from time to time. Following the curing period, specimens were kept in the oven for 24 h at 70 °C to expel the moisture. Further, they were air dried at room temperature for 24 h prior to coating them with the selected surface coatings.

2.3. Surface preparation

The concrete and mortar specimens were cleaned as per the manufacturer's specifications prior to the application of the coatings. After preparation of the surface, the coatings were applied with a brush as per the manufacturer's instructions.

2.4. Coatings used

The concrete coatings were selected to represent the following five generic types:

(i) Acrylic coatings, AC,
(ii) Polymer emulsion coatings, PE,
(iii) Epoxy resin coatings, EP,
(iv) Polyurethane coatings, PU and
(v) Chlorinated rubber coatings, CR.

Each generic type was represented by two coatings procured from different manufacturers. After surface preparation, the coatings were applied as per the manufacturer's instructions.

3. Test procedure

3.1. Chloride permeability

The selected surface coatings were applied on the two faces of 75 mm diameter and 50 mm thick concrete discs. A rapid set epoxy coating was applied on the curved surfaces of the discs to make them impermeable. The samples were, then, saturated with water, under vacuum as per the procedures outlined in ASTM C 1202.

3.2. Chemical resistance

Cement mortar specimens measuring 25 × 25 × 25 mm^3 were coated on all the faces with the selected coating and then immersed in a 2.5% sulfuric acid solution. The coated specimens were visually inspected at regular intervals for signs of coating deterioration. The extent of coating deterioration was evaluated on a qualitative rating varying from 1 to 5. A rating of 1 would indicate no deterioration while a rating of 5 would indicate complete deterioration of the coating. Table 2 summarizes the rating system.

3.3. Chloride diffusion

The selected surface coatings were applied on one face of the concrete specimens. Wax was applied on the curved surface and the uncoated face of the concrete specimen to ensure unidirectional diffusion of chloride ions and then they were immersed in 5% sodium chloride solution for three months. After this period, the specimens were removed and cleaned and concrete discs of 5 mm thickness were obtained at depths of 5, 20, 50, 75 and 100 mm. These discs were crushed to obtain concrete powder passing ASTM # 100 sieve. Five grams of this sample was placed in a beaker to which 50 ml of hot distilled water was added. The beaker was covered and the contents were allowed to cool for 24 h. The mixture was then filtered into a flask and the filtrate was made up to 150 ml by adding more distilled water. 0.2 ml of the filtrate was added to 9.8 ml of distilled water. Then, 2 ml of 0.25 M ferric ammonium sulfate and 2 ml of mercuric thiocyanate were added to it. This solution was then poured into a test tube that was placed in the spectrophotometer to measure the absorbance. A blank solution was prepared and its absorbance was also measured. The chloride concentration was calculated using the chloride calibration curve prepared earlier utilizing a chloride solution of known concentration.

The chloride concentration was then plotted against depth. The coefficient of chloride diffusion in each of the selected coatings was determined from the chloride profile by solving Fick's second law of diffusion [16,17], as shown below

$$\frac{C_x}{C_s} = 1 - \operatorname{erf}\left\{\frac{x}{2\sqrt{D_e t}}\right\} \tag{1}$$

where, C_x is the chloride concentration at depth x (%), C_s is the chloride concentration at the concrete surface (%), x is the depth from concrete surface (mm), t is the time (s), and; D_e is the effective chloride diffusion coefficient (cm^2/s).

3.4. Water absorption

The selected coatings were applied on all the faces of 50 mm ∅ and 75 mm long mortar specimens. The specimens were weighed after the coating had dried and then placed in a water tank on a wire mesh such that only the bottom face was always in contact with water. The increase in weight of the samples due to absorption of water was recorded at periodic intervals up to 56 h and plotted against time to evaluate the moisture vapor transmission resistance of the coated and uncoated samples.

Table 2
Qualitative rating for coating deterioration in specimens exposed to 2.5% H_2SO_4

Rating	Description
1	Coating intact
2	Corners damaged
3	Corners and edges deteriorated
4	Corners, edges and some surface damage
5	Coating delamination and/or Dissolution

4. Results and discussion

4.1. Chloride permeability

Table 3 shows the total charge passed through the concrete specimens coated with the selected coatings. The ASTM C 1202 classification based on the total charge passed is also provided in this table. The chloride

Table 3
Total charge passed through the coated and uncoated concrete specimens

Coating	Charge passed (Coulombs)	ASTM C 1202 classification
Acrylic coating, AC1	163.67	Very low
Acrylic coating, AC2	69.71	Negligible
Polymer emulsion coating, PE1	703.4	Very low
Polymer emulsion coating, PE2	514.67	Very low
Epoxy coating, EP1	7.32	Negligible
Epoxy coating, EP2	159.93	Very low
Polyurethane coating, PU1	39.09	Negligible
Polyurethane coating, PU2	6.36	Negligible
Chlorinated rubber coating, CR1	49.83	Negligible
Chlorinated rubber coating, CR2	38.7	Negligible
None	975.47	Low

permeability of the concrete specimens coated with the chlorinated rubber coatings was in the range of 39–50 coulombs, while it was in the range of 6–40 coulombs in the polyurethane coatings. In the epoxy coated concrete specimens, the total charge passed varied from 7 to 160 coulombs, whereas in the concrete specimens coated with acrylic coatings the total charge passed varied from 70 to 164 coulombs. The total charge passed in the concrete specimens coated with the polymer emulsion coatings was in the range of 515–713 coulombs, whereas the total charge passed in the uncoated concrete specimens was 975 coulombs.

According to ASTM C 1202 classification the chloride permeability of all the coated concrete specimens was ‘negligible’ except in those coated with coatings ACI, PE1, PE2 and EP2. The chloride permeability of the specimens coated with these coatings was very low. The chloride permeability of the uncoated concrete specimens was ‘low’.

The chloride permeability of the concrete specimens coated with polyurethane, chlorinated rubber, epoxy and acrylic coatings was almost one-tenth of that of the uncoated concrete and one-fifth of the concrete specimens coated with the polymer emulsion coatings.

For a concrete of similar composition the chloride permeability of a coating depends primarily on the porosity of the film. Lower the porosity of the film, lower will be the charge passing through the film. The porosity, in turn, depends on the volume of solids, dry film thickness and the type of binder used in the coating. The polyurethane and epoxy coatings provide resistance to the ingress of aggressive ions because they are solvent-based and as the coating cures, it leaves behind a tough film with low porosity.

The performance of the selected coatings, as per chloride permeability test (ASTM C 1202) is in the following descending order:

(i) Polyurethane coating, PU2
(ii) Epoxy resin coating, EP1
(iii) Chlorinated rubber coating, CR2
(iv) Polyurethane coating, PU1
(v) Chlorinated rubber coating, CR1
(vi) Acrylic coating, AC2
(vii) Epoxy resin coating, EP2
(viii) Acrylic coating, AC1
(ix) Polymer emulsion coating, PE2
(x) Polymer emulsion coating, PE1

4.2. Water absorption

The total weight gained by the coated and uncoated specimens after 56 h is shown in Table 4. As expected, the uncoated cement mortar specimens absorbed water at a very rapid rate and after 56 h the total absorption was about 5% by weight. The water absorption in the cement mortar specimens coated with polymer emulsion coatings was in the range of 3.3–3.4%, which was more than the water absorption noted in the specimens coated with the other coatings. The specimens coated with acrylic coatings absorbed 0.23–1.46% water while those coated with the chlorinated rubber absorbed water in the range of 0.76–1.04%. The water absorption in the samples coated with the polyurethane coatings was about 0.21–1.83% and in the epoxy coated specimens it was in the range of 0.27–1.3%.

Minimum weight gain was noted in the cement mortar specimens coated with the epoxy and polyurethane coatings. However, a large variation in the performance of the coatings of the same generic type, procured from different manufacturers, was noted. Hence, it is advised that when selecting a coating for moisture vapor resistance, each coating should be tested individually before use and the generic type should not be the sole criterion for selecting a coating.

The data in Fig. 1 were utilized to calculate the rate of water absorption and sorptivity of the coated and uncoated mortar specimens using Eqs. (2) and (3).

$$\text{Rate of water absorption} = W_w/(A_c t) \quad (2)$$

Table 4
Weight gain in the coated and uncoated cement mortar specimens after 56 h of immersion in water

Coatings	Weight gain (%)
Acrylic coating, AC1	0.23
Acrylic coating, AC2	1.46
Polymer emulsion coating, PE1	3.42
Polymer emulsion coating, PE2	3.32
Epoxy coating, EP1	1.30
Epoxy coating, EP2	0.27
Polyurethane coating, PU1	0.21
Polyurethane coating, PU2	1.83
Chlorinated rubber coating, CR1	0.76
Chlorinated rubber coating, CR2	1.04
None	4.78

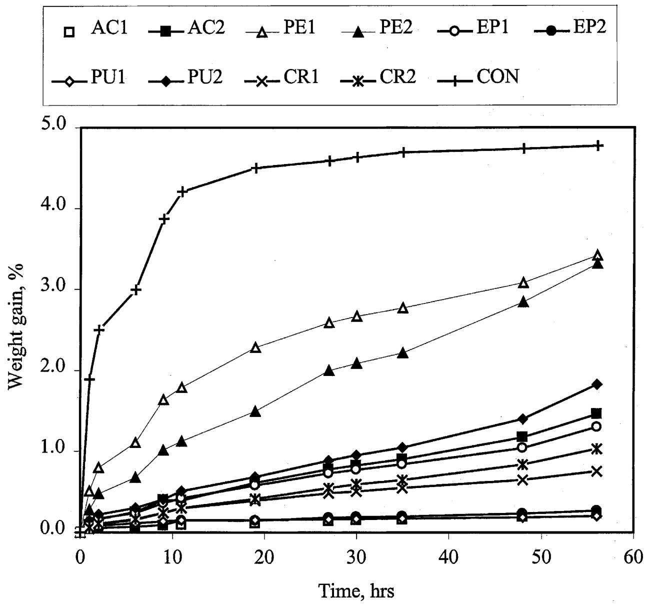

Fig. 1. Variation of the weight gained by the coated and uncoated mortar specimens due to water absorption.

$$\text{Sorptivity} = V_w/(A_c\sqrt{t}) \tag{3}$$

where, W_w is weight gained by the specimen, A_c is cross-sectional area of each specimen, t is time of exposure and V_w is volume of water adsorbed by the specimen.

These data are presented in Table 5. The rate of water absorption in the cement mortar specimens coated with polymer emulsion coatings was in the range of 56–60 g/m^2/h, whereas in the uncoated mortar specimens it was 63.4 g/m^2/h. The mortar specimens coated with acrylic coatings absorbed water at a rate of 5–30 g/m^2/h and those coated with polyurethane coatings absorbed water at a rate of 4–37 g/m^2/h. The rate of water absorption in the mortar specimens coated with chlorinated rubber coatings was in the range of 16–22 g/m^2/h. As expected, the water absorption in the epoxy-coated specimens was the lowest, being in the range of 4–27 g/m^2/h due to a dense film formed on the specimens coated with these coatings.

Table 5
Rate of absorption and sorptivity in the coated and uncoated cement mortar specimens

Coatings	Absorption rate (g/m^2/h)	Sorptivity (mm/$\sqrt{\mathrm{h}}$)
Acrylic coating, AC1	4.4	0.03
Acrylic coating, AC2	30.6	0.23
Polymer emulsion coating, PE1	55.6	0.40
Polymer emulsion coating, PE2	59.7	0.45
Epoxy coating, EP1	26.9	0.20
Epoxy coating, EP2	4.9	0.04
Polyurethane coating, PU1	3.4	0.03
Polyurethane coating, PU2	36.6	0.27
Chlorinated rubber coating, CR1	16.1	0.12
Chlorinated rubber coating, CR2	22.6	0.17
None	63.4	0.47

Research [18] on the water absorption of specimens coated with acrylic and polyurethane coatings using the modified ISAT has shown that the rate of water absorption in the treated samples was about 40 g/m^2/h, whereas in the untreated samples it was 350 g/m^2/h. Dulaijan et al. [10,11] immersed the coated and uncoated mortar specimens for 672 h in water and observed that the gain in weight of the uncoated specimens was 3% as compared to 0.6–2.6% in the specimens coated with the epoxy resin-based coatings.

The performance of the selected coatings under partially submerged conditions was in the following descending order:

(i) Polyurethane coating, PU1
(ii) Acrylic coating, AC1
(iii) Epoxy resin coating, EP2
(iv) Chlorinated rubber coating, CR1
(v) Chlorinated rubber coating, CR2
(vi) Epoxy resin coating, EP1
(vii) Acrylic coating, AC2
(viii) Polyurethane coating, PU2
(ix) Polymer emulsion coating, PE2
(x) Polymer emulsion coating, PE1

4.3. Chloride diffusion

Figs. 2–7 show the chloride profiles for the coated and uncoated concrete specimens. The chloride concentration in all the specimens decreased with depth. Further, the chloride concentration in the uncoated concrete specimens was more than that in the coated concrete specimens at all depths. The chloride concentration profiles were utilized to calculate the chloride diffusion coefficients by solving Fick's second law of diffusion. These data are summarized in Table 6.

The chloride diffusion coefficient for the uncoated concrete specimens was more than those for the coated concrete specimens. This value in the uncoated concrete

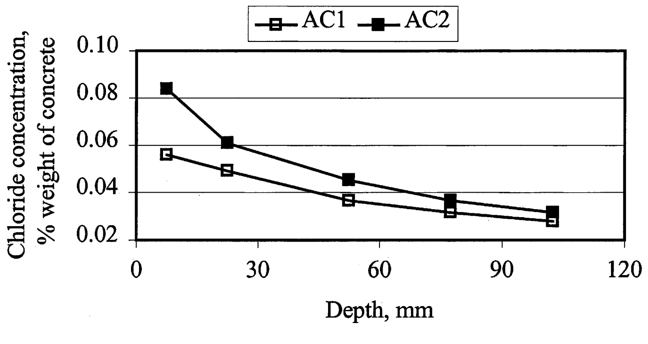

Fig. 2. Chloride profile for the concrete specimens coated with acrylic coatings.

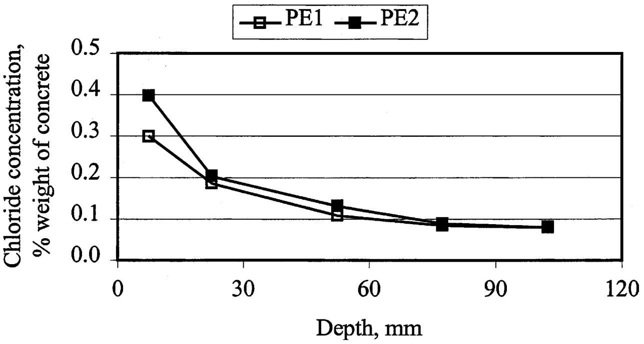

Fig. 3. Chloride profile for the concrete specimens coated with polymer emulsion coatings.

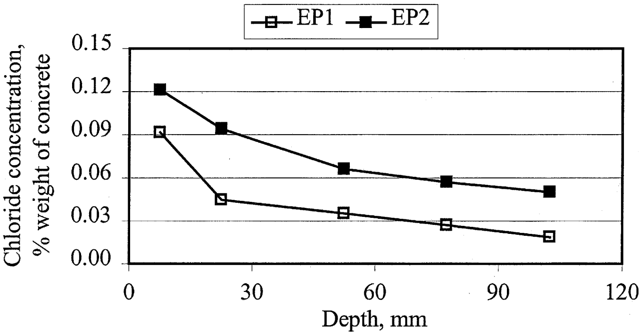

Fig. 4. Chloride profile for the concrete specimens coated with epoxy coatings.

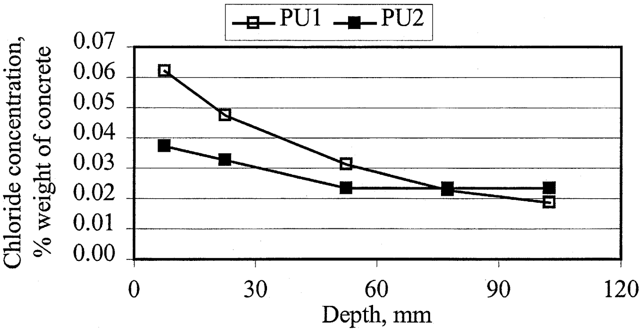

Fig. 5. Chloride profile for the concrete specimens coated with polyurethane coatings.

specimen was 19.2×10^{-8} cm^2/s. In the specimens coated with acrylic emulsion coatings, it was in the range of 2.1×10^{-8} to 3.5×10^{-8} cm^2/s while it was in the range of 8.4×10^{-8} to 16×10^{-8} cm^2/s for the specimens coated with polymer emulsion coatings. Chloride diffusion coefficients were in the range of 2.6×10^{-8} to 7.7×10^{-8} cm^2/s for concrete specimens coated with epoxy coatings and they were in the range of 8.4×10^{-8} to 9.6×10^{-8} cm^2/s for the specimens coated with the chlorinated rubber coatings. The lowest chloride diffusion coefficients were noted for the specimens coated with polyurethane coatings. These values were in the range of 0.7×10^{-8} to 1.8×10^{-8} cm^2/s.

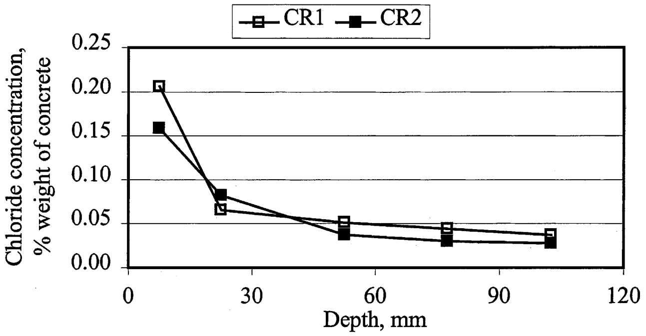

Fig. 6. Chloride profile for the concrete specimens coated with chlorinated rubber coatings.

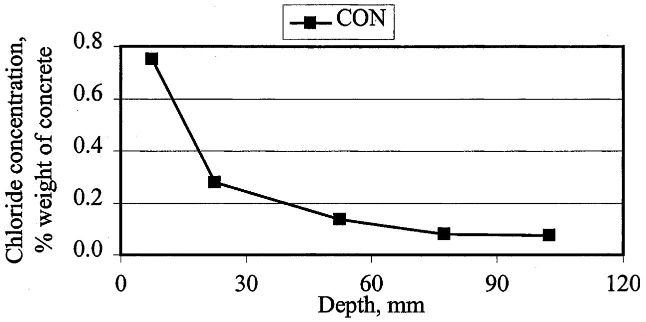

Fig. 7. Chloride profile for the uncoated concrete specimens.

Table 6
Chloride diffusion coefficients for the coated and uncoated concrete specimens

Coating	Coefficient of chloride diffusion (10^{-8} cm^2/s)
Acrylic coating, AC1	2.08
Acrylic coating, AC2	3.49
Polymer emulsion coating, PE1	8.40
Polymer emulsion coating, PE2	15.94
Epoxy coating, EP1	7.67
Epoxy coating, EP2	2.59
Polyurethane coating, PU1	1.83
Polyurethane coating, PU2	0.70
Chlorinated rubber coating, CR1	9.56
Chlorinated rubber coating, CR2	8.40
None	19.18

The polyurethane and acrylic coatings were ≈10 times more effective in resisting the diffusion of chloride ions as compared to the uncoated concrete specimens. The chlorinated rubber coatings were half as effective as the epoxy coatings and the chloride concentration in the concrete specimens coated with the polymer emulsion coatings was 60–70% of those in the uncoated concrete specimens.

The superior performance of coatings in decreasing chloride diffusion has been reported by other researchers [10,11,19,20].

The efficiency of the coatings in preventing the ingress of chloride ions can be further emphasized by calculating the concrete cover required over the reinforcement for an estimated service life of 50 years. The mathematical model proposed by Poulsen et al. [21], given in Eq. (4), was utilized to estimate the minimum concrete cover that would be required for each coating if the chloride concentration at the end of 50 years was to be <0.06% by weight of concrete, at the level of the rebar, in concrete with a w/c ratio of 0.45.

$$c_{\min} = \sqrt{4 t_{\mathrm{LT}} D_{\mathrm{a}}} \times \mathrm{inv}\psi_{\mathrm{p}} \left\{ \frac{C_{\mathrm{cr}} - C_{\mathrm{i}}}{S(t_{\mathrm{LT}} D_{\mathrm{a}})^{p}} \right\} \tag{4}$$

where, $c_{\min}$ is the minimum cover to reinforcement (mm), t_{LT} is the service lifetime (years), D_{a} is the achieved diffusion coefficient, ψ_{p} is a function tabled by Mejlbro [22], C_{cr} is the critical chloride concentration (%), C_{ci} is the initial chloride concentration in the concrete (%) and S and p are the constants chosen by Swamy et al. [23] for concrete exposed to land-splash zone.

The minimum concrete cover for the rebar required to prevent the ingress of chloride ions to the rebar surface within a service life of 50 years is summarized in Table 7 for the coated and uncoated concrete specimens. It can be seen that the concrete cover reduces drastically if the coating being applied is effective in preventing the diffusion of chloride ions to the substrate. Uncoated concrete would require a cover of almost 120 mm to prevent the diffusion of the chlorides to the rebar surface whereas a cover of only 10–20 mm would suffice if the concrete is coated with a polyurethane coating. A cover of 28 to 60 mm would be required for epoxy coatings while for chlorinated rubber coatings the cover could range from 62 to 67 mm. Concrete coated with acrylic coatings would require a cover of 27–38 mm and if polymer emulsions are used the cover could range from 63 to 100 mm.

The effectiveness of the coating can also be emphasized by calculating the time to initiation of reinforcement corrosion in a concrete structure with a cover to reinforcement of 50 mm. A mean surface chloride concentration of 0.36%, by weight of cement proposed by Swamy [23], was utilized and the time required for the chloride concentration at the rebar level to reach 0.06%, by weight of concrete, was calculated using Eq. (1). The time to initiation of reinforcement corrosion for the coated and uncoated concrete specimens are shown in Table 8. Reinforcement in the uncoated concrete specimens would start corroding after about 1 year from the time of casting, whereas, in the concrete specimens coated with polyurethane coatings this value would range from 11 to 30 years. In the concrete specimens coated with epoxy coatings the rebar could be safe up to 3–8 years and in the concrete specimens coated with acrylic coatings the time to initiation of corrosion would be in the range of 6–10 years. In the concrete specimens coated with polymer emulsion coatings rebar corrosion will initiate within 1–2.5 years.

Table 7
Minimum cover to reinforcement for a service life of 50 years

Coating	Minimum cover (mm)
Acrylic coating, AC1	27.8
Acrylic coating, AC2	37.5
Polymer emulsion coating, PE1	62.8
Polymer emulsion coating, PE2	96.1
Epoxy coating, EP1	60.0
Epoxy coating, EP2	28.4
Polyurethane coating, PU1	19.5
Polyurethane coating, PU2	9.4
Chlorinated rubber coating, CR1	67.0
Chlorinated rubber coating, CR2	62.8
None	119.5

Table 8
Time to initiation of reinforcement corrosion with a concrete cover of 50 mm

Coating	Time to initiation of corrosion (years)
Acrylic coating, AC1	9.96
Acrylic coating, AC2	5.94
Polymer emulsion coating, PE1	2.47
Polymer emulsion coating, PE2	1.29
Epoxy coating, EP1	2.70
Epoxy coating, EP2	7.99
Polyurethane coating, PU1	11.3
Polyurethane coating, PU2	29.59
Chlorinated rubber coating, CR1	2.17
Chlorinated rubber coating, CR2	2.47
None	1.08

The performance rating of the selected coatings in decreasing the diffusion of chloride ions, thereby delaying initiation of reinforcement corrosion, can be rated in the following descending order:

(i) Polyurethane coating, PU2
(ii) Polyurethane coating, PU1
(iii) Acrylic coating, AC1
(iv) Epoxy resin coating, EP2
(v) Acrylic coating, AC2
(vi) Epoxy resin coating, EP1
(vii) Chlorinated rubber coating, CR2
(viii) Polymer emulsion coating, PE1
(ix) Chlorinated rubber coating, CR1
(x) Polymer emulsion coating, PE2

4.4. Chemical resistance

The chemical resistance of the selected coatings was evaluated by visual inspection of the coated cement mortar specimens exposed to 2.5% sulfuric acid. The

Table 9
Deterioration ratings for the coated and uncoated mortar specimens exposed to 2.5% H_2SO_4

Coating	Deterioration rating, after (days)				
	3	7	21	30	60
Acrylic coating, AC1	1	2	2	3	3
Acrylic coating, AC2	2	3	3	3	3
Polymer emulsion coating, PE1	3	3	4	5	5
Polymer emulsion coating, PE2	3	3	4	4	5
Epoxy coating, EP1	1	1	1	1	2
Epoxy coating, EP2	1	1	2	2	2
Polyurethane coating, PU1	1	1	1	2	2
Polyurethane coating, PU2	1	1	1	1	2
Chlorinated rubber coating, CR1	2	2	3	4	5
Chlorinated rubber coating, CR2	2	2	3	4	4
None	5	5	5	5	5

mortar specimens coated with polymer emulsion coatings deteriorated very rapidly and they were as bad as the uncoated concrete specimens only after 30 days. The chlorinated rubber coatings also peeled off the surface of the specimens as early as seven days. The specimens coated with acrylic coatings exhibited failure at the edges in a short time. The polyurethane and epoxy coatings were relatively intact with just the corners of the specimens damaged even after 60 days.

The extent of coating deterioration was evaluated on a qualitative rating varying from 1 to 5. A rating of 1 would indicate no deterioration while a rating of 5 would indicate complete deterioration of coating. This information is summarized in Table 9.

The chemical resistance of the selected coatings was in the following descending order:

(i) Epoxy coating, EP1
(ii) Epoxy coating, EP2
(iii) Polyurethane coating, PU1
(iv) Polyurethane coating, PU2
(v) Acrylic coating, AC1
(vi) Acrylic coating, AC2
(vii) Chlorinated rubber coating, CR1
(viii) Chlorinated rubber coating, CR2
(ix) Polymer emulsion coating, PE1
(xi) Polymer emulsion coating, PE2

5. Conclusions

The polyurethane coatings were highly effective in reducing the electrical resistivity of concrete, as was evidence by the chloride permeability and water permeability values. The epoxy and chlorinated rubber coatings also allowed only a negligible charge to pass through. The chloride permeability of acrylic and polymer emulsion coatings was also very low according to ASTM C 1202.

The epoxy and polyurethane coatings were the best in decreasing the absorption of water into concrete exhibiting low absorption rates and sorptivity. The acrylic and chlorinated rubber coatings also gained $<2\%$ water, by weight, after 56 h but the specimen coated with polymer emulsion coatings gained more than 3% by weight, due to water absorption.

The epoxy and polyurethane coatings were found relatively intact, with just the corners of the specimens damaged, after 60 days in 2.5% sulfuric acid solution, whereas all the other coatings had deteriorated completely by that time. The polymer emulsion coatings dissolved in the acid and the chlorinated rubber coatings peeled off the substrate within a short period.

The least coefficient of chloride diffusion was measured in the concrete specimens coated with the polyurethane coatings followed by the specimens coated with epoxy and acrylic coatings. Polymer emulsion and chlorinated rubber coatings were the least effective in preventing the diffusion of chloride ions in concrete.

The chloride diffusion data were utilized to calculate the time to initiation of reinforcement corrosion. These data indicate that reinforcement in the uncoated concrete specimens would start corroding after about 1 year while it will take about 11–30 years for the steel bars to corrode in the concrete specimens coated with polyurethane coatings.

Polyurethane and epoxy-based concrete surface coatings have performed better than other generic types of coatings investigated in this study. However, a wide variation in the performance was noted within the coatings of same generic type.

6. Recommendations for selection of coatings

Based on the data developed in this study, coatings for the commonly occurring service environments are as suggested below:

Service condition	Recommended coating in order of preference
Chemical attack	Epoxy, polyurethane, acrylic
Chloride	Polyurethane, chlorinated rubber, epoxy
Wet	Epoxy, chlorinated rubber, acrylic

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